Demystifying Capacitors, Coils, and Antenna Tuners—Part 1

In a blend of old and new, K4TWJ takes over where W6TNS's "In Theory" column left off last October, but with a new title and a somewhat broader focus. Where it goes from here is up to you!

A Few Words of Introduction...

I was elated when Rich Moseson told me that Dave Ingram had agreed to take over the "In Theory" column. I cannot think of a person more qualified than Dave to explain how things work and their relationship to ham radio.

I've known Dave Ingram for many years. When I edited a now-defunct ham radio publication, Dave was always there, on time, with material that was interesting to the readers. He received more fan mail from them than my editorials did!

Occasionally Dave used to send me items that were products of his bountiful brain. I will always value his rebel flag QSL that identifies my car in crowded parking lots. But most of all I treasure the little wooden roof with the thumbtacks under it. When I asked Dave what it was, he supplied the obvious answer, "A tax shelter."

Good luck, Dave, the column is in great hands. Looks like you are once again working for a great editor!

73 Don, W6TNS

I understand that Don Stoner will add some opening commentary to this new theory 'n practice column, but I'm unsure about what he will say. Hopefully, it won't be described as a direct continuation of Don's "In Theory" column, as I feel no one can replace Don, but only succeed him.

Don is an original and a classic, and his dedication to the hobby covers many decades. He helped usher transistors into amateur radio with his neat little "Semiconductor Space Spanner" during the 1950s (see Photo A); assisted in launch efforts for amateur radio's first satellite, OSCAR I, in the 1960s; and he was recognized by AMSAT with the

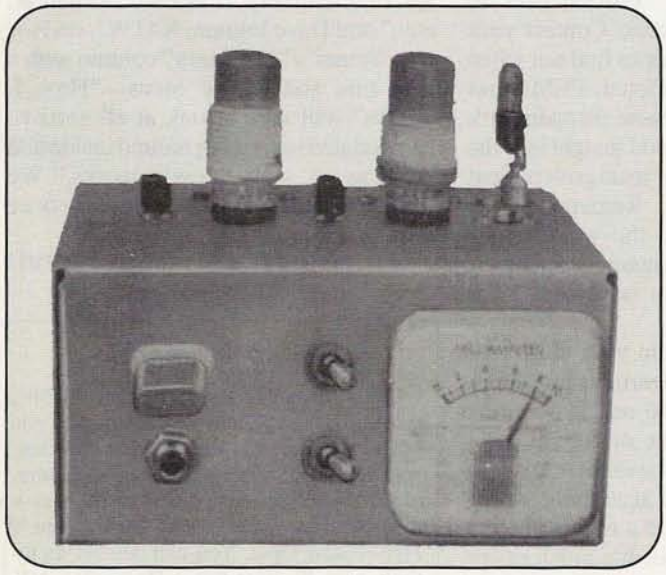

Photo A. Original (and authentically faded with age!) view of Don Stoner's famous Semiconductor Space Spanner transmitter of the 1950s. The little two-transistor delight introduced solid-state electronics to radio amateurs worldwide.

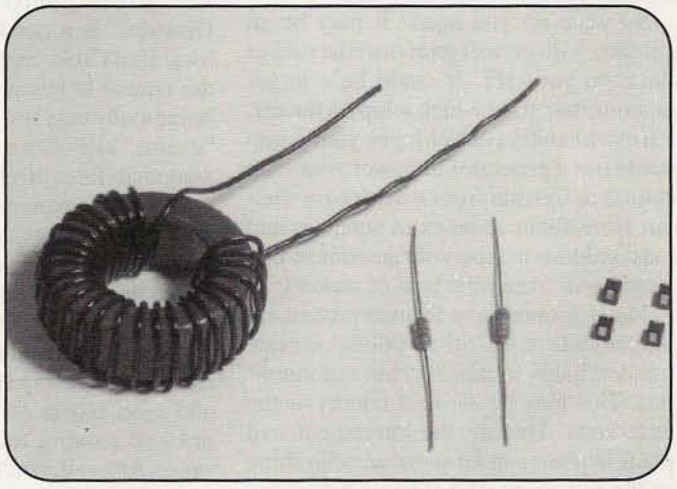

Photo B. Three popular types of "fixed" inductors: A toroidal core with "X number" of turns to yield a desired inductance, a prewound/molded inductor, and a "chip" inductor. Although quite different in size and shape, all three types can yield the same inductance. Chip inductors are often used in FM handhelds and compact transceivers using SMT, or Surface Mount Technology. (Photos B through E courtesy David Branch, KB5VKY, of MFJ Enterprises, Inc.)

By Dave Ingram, K4TWJ

Stoner Cup Challenge Award in the '80s. Don also founded the National Amateur Radio Association during the '90s, plus much more. It is indeed an honor to progress (with a few diversions!) along the general path Don pioneered here in *CQ VHF*.

How far off the path and how many diversions we'll pursue depend on requests from you, our readers. I'm maintaining high flexibility to match your input, so drop me a note on various topics or subjects you would like to see featured here. Meanwhile (and as a thought-inspiring example), let's continue on from Don's introduction of capacitors and inductors in his final column and discuss how those two components are used in popular amateur radio accessories: antenna tuners.

More Notes on Capacitors and Inductors

As Don explained in his October, 1997, "In Theory" column, two unique properties of capacitors are the ability to block DC while passing AC and the ability to work in conjunction with inductors to tune circuits. Looking more closely at this, we find the amount of AC a capacitor passes depends on its value, measured in microFarads (µF) or picoFarads (pF), and the frequency of an applied AC signal. Generally speaking, a small value capacitor will pass a high frequency, but it will not pass a low frequency. A large value capacitor, however, can pass very low frequencies. In other words, capacitors exhibit a sort of "AC resistance," which we call *reactance*. That is why 10- or 250-pF capacitors are used in antenna tuners for VHF and HF, while 200- to 5000-µF capacitors (rather than .01 µF) are used as filters in (60 Hz) power supplies. (I'll expand on how capacitors act like low value resistances to AC in next month's discussion of power supplies.)

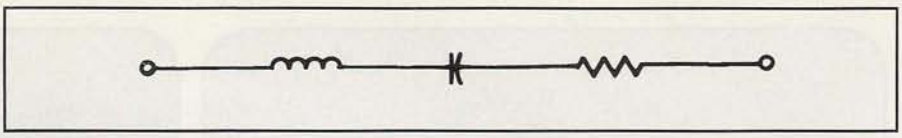

Figure 1. Since antennas exhibit properties of capacitance, inductance, and resistance, they are electrically equivalent to a series tuned circuit. At resonance, the coil's reactance and the capacitor's reactance cancel and leave only the (radiation) resistance. See discussion in text.

Coils, or inductors, differ from capacitors in that they pass DC and block or "choke out" AC. The amount of AC choked out depends on the coil's value, measured in milliHenrys (mH) or microHenrys (µH), and the frequency of the applied AC signal. A small value coil can choke high frequencies, whereas a large value coil is necessary to choke low frequencies. As an example, a small choke is usually located between a transmitter's RF amplifier section and its DC input socket. This choke prevents RF energy from reaching the power supply. As another example, old-style power supplies used with vacuum tube rigs often included a large and expensive inductor or choke to remove small amounts of AC hum not removed by large filter capacitors.

Since chokes are quite expensive, many new-style power supplies use larg-

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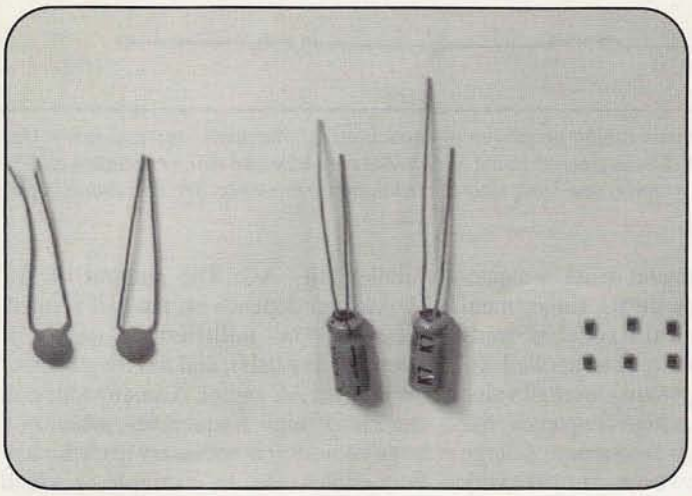


Photo C. Three popular types of "fixed" capacitors: disc (for RF and bypass applications), electrolytic (typically used in power supply-related circuits), and "chip" capacitors for SMT.

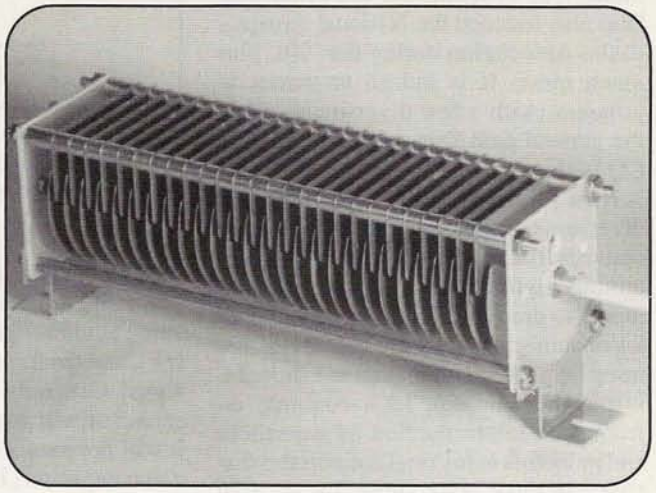


Photo D. Traditional style of variable capacitor. Fixed plates are called stator; adjustable plates that mesh in it are called rotor. The number of both types of plates influences total capacity.

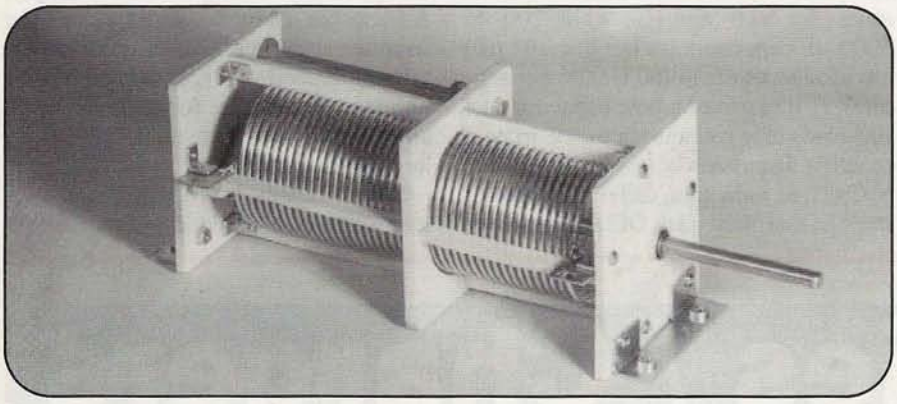
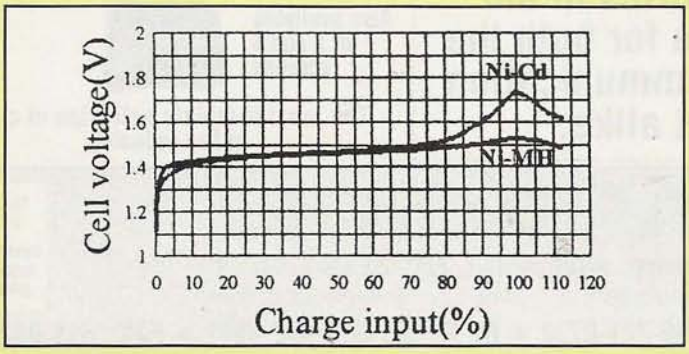


Photo E. Inductors used with antenna tuners are wound on a form or left open-air style. They may be made adjustable by turning the coil while a small metal wheel "rides" in between turns.

Oops...

Last month's article, "An NiMH Warning: Don't Toast Your Battery!" by Gordon West, WB6NOA, contained an incorrect graph. What was supposed to show the charging curves of nickel metal hydride (NiMH) versus nickel cadmium (NiCd) batteries—and the voltage "elbows" at full charge (the "elbow" is much more pronounced in a NiCd than an NiMH, making it easy for a NiCd charger to miss the full-charge point on an NiMH cell)—actually showed the comparative discharge curves of the two types of cells. The correct graph, still courtesy of NEXcell Battery Co., Ltd., appears here. We apologize for the error.



er filter capacitors and active regulators rather than including a choke. Some popular types of capacitors and inductors are shown in Photos B through E to help you identify them in amateur radio gear.

At this point, you might understandably ask why, if different value capacitors and inductors exhibit different AC resistances or "reactances," is one rather than the other is used in a circuit. Without delving into heavy technical details, a capacitor's capacity reactance (Xc) can be used to cancel a coil's inductive reactance (Xl) (*that's a capital "X" and a small "L," not a number "1"—ed.)* and vice versa. This is because properties of the two reactances are opposites in phase relationships (See "Technically Speaking," elsewhere in this column). When or where are such "cancellation effects" beneficial? An antenna tuner is a familiar example, but before discussing how tuners work, let's consider when and why one is needed.

Antennas: Large Tuned Circuits

Although we visualize antennas as radiators and interceptors of signals, our transceivers "see" them as series-tuned circuits (see Figure 1). How so? The length of an antenna's wire or driven element is its inductance, and the distance or spacing between its wire or driven element and ground (plus other nearby objects) is its capacitance. When those two opposite reactances (Xl and Xc) are equal, the antenna is said to be *resonant*.

When an antenna is resonant, it cheerfully accepts RF energy routed or cabled

Technically Speaking

As mentioned in the main text, capacitive and inductive reactances are opposites in phase relationships and (assuming equal values) one can cancel the other. How so?

The time required for a capacitor to store a charge as electrostatic lines of force causes a phase shift, or delays applied voltage 90 degrees with respect to applied current (illustrated vectorially in Figure 2A). Likewise, the time period required for an inductor to store energy as expanding lines of electromagnetic force delays applied current 90 degrees with respect to applied voltage (Figure 2B). A resistor does not produce an electromagnetic or electrostatic field, thus its applied voltage and current remain in phase. Current remains constant and voltage divides among components in a series circuit, thus current is a reference vector.

Figure 2C shows a resistor's in-phase current as a reference vector overlaying capacitance and inductance. El and Ec are 180 degrees apart; if the length of their vectors (their out-of-phase voltages) are equal, they cancel and only the resistor's in-phase voltage and current remain. An easy way to remember phase relations is "Eli The Ice Man"—voltage is ahead of current in a coil and current "comes before voltage" in a capacitor.

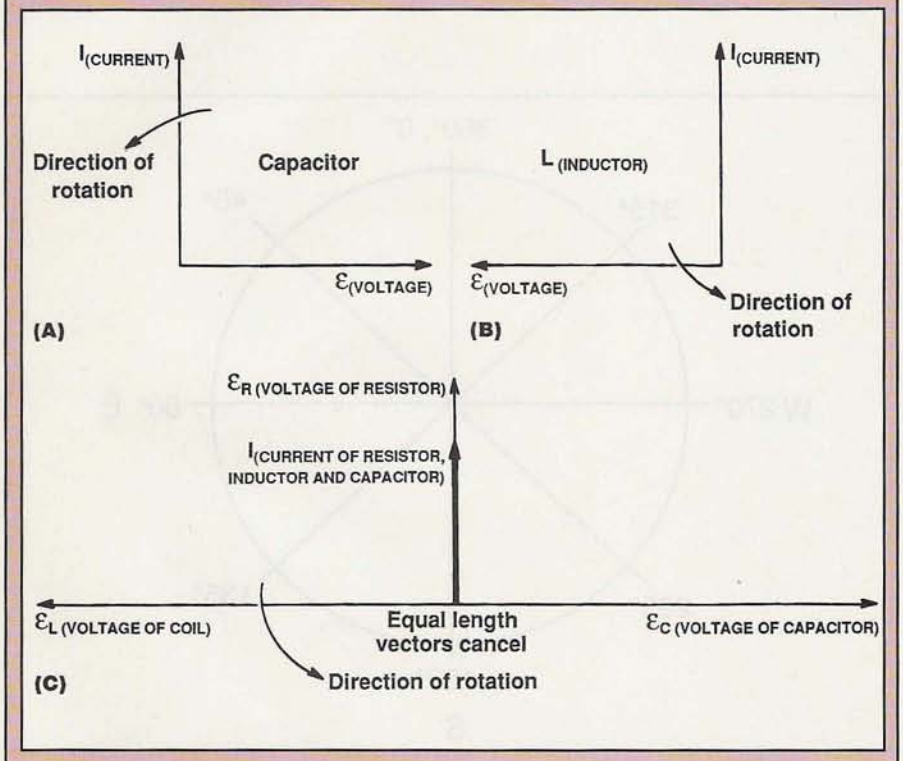


Figure 2A. The time required for a capacitor to store a charge causes its voltage to be 90 degrees out of phase with its current. Figure 2B. The same time delay in an inductor causes its voltage to lead its current by 90 degrees. Note that the inductor's voltage (El) is 180 degrees out of phase with the capacitor's voltage (Ec) in Figure 2A. Figure 2C. Put Figures 2A and 2B together and you see that El and Ec cancel each other out in a resonant circuit, leaving you with the voltage of the resistor (Er), which remains in phase with the constant current of the inductor, capacitor and resistor.

to it from a transmitter or transceiver. Ah, but exact resonance is quite difficult to achieve in reality, and it is only maintained over a very limited frequency range. When an antenna is not precisely resonant, a portion of its (cabled-in) RF energy is reflected back through its feedline or cable to the transceiver. The ratio of forward to reflected power is what we call *SWR* (Standing Wave Ratio) and, as you know, SWRs above 1.6:1 or 2.0:1 (depending on your rig) cause a transceiver or amplifier to "cut back" or reduce its power output for self-protection. When that happens, we have three general options: live with the high SWR and reduced output (pity the little rig!), readjust the antenna's dimensions and matching sections, or add an antenna tuner.

"The length of an antenna's wire or driven element is its inductance, and the distance or spacing between its wire or driven element and ground (plus other nearby objects) is its capacitance."

"Ah, but commercially-made antennas are resonant and pretuned," you say: "I just adjust it to my preferred operating range and install it, right?" Maybe, maybe not (As "Dirty Harry" says, "Do you feel lucky, kid?"). Manufacturers strive to cut their antennas' dimension for mating with "average" amateur radio applications, but every installation is unique. One antenna might be installed on a roof or chimney, another might be on a tower 50 or 70 feet high, one might be near (or in!) trees, one might parallel metal siding on a house or another antenna, and ground conductivity can vary in each case. All such factors alter an antenna's Xl/Xc balance, shift its resonant frequency, and thus produce an above-normal SWR.

An antenna tuner solves the problem. It does not "retune your antenna" so to speak, but lets you add an adjustable amount of inductive or capacitive reactance to cancel undesired capacitive or inductive reactance at the transceiver's end of the feedline/coax cable. Your transceiver then "sees" an optimum match and comfortably delivers its full output power to the antenna system—that is *if* the antenna's radiation resistance is near 50 ohms.

Whaddaya Mean, IF?

Is your antenna's impedance 50 ohms? "Aren't all popular styles of antennas 50 ohms?" you reply. Stay tuned! Next month's column has some interesting answers to those questions. Meanwhile, drop me a note and tell me some of the topics or areas you would like to see covered in this "How It Works" column.

73, Dave, K4TWJ

Demystifying Capacitors, Coils, and Antenna Tuners—Part 2

Last month, Dave discussed the basics of capacitance and inductance. Now, he'll show us how they work together in an antenna tuner.

Greetings again, friends! I'm back with the second part of our discussion on capacitors, inductors, and antennas, and I have some good "hands-on" views that I'm sure you'll find interesting and informative. Who knows? Maybe the views may even inspire you to "roll your own" antenna tuner for home or mobile use.

Appealing idea? Here's the main point to keep in mind: Transmitting-type capacitors with wide spacing between their plates can be pricey when purchased new or in pairs. Check hamfest fleamarkets for special bargains—but be sure you're getting useful goods before walking away with a big grin. Whether using a professionally made or homebrewed tuner, however, it's always beneficial to understand the "How It Works" theory behind the unit. With that thought in mind, let's pick up where we left off last time.

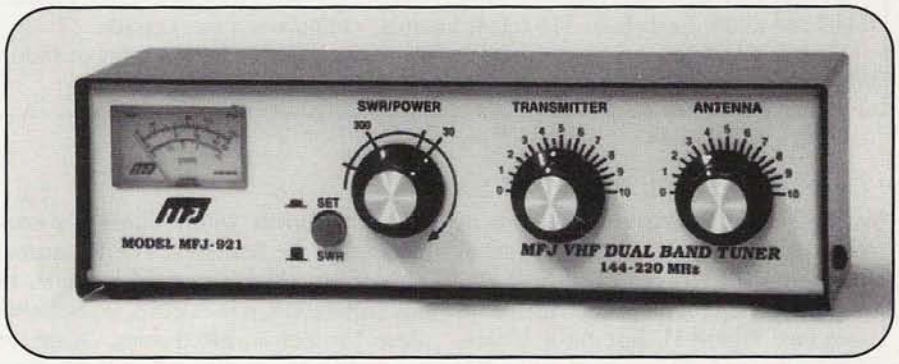


Photo A. Compact MFJ-921 2-meter/222-MHz antenna tuner. This unit has a wide impedance matching range, built-in SWR meter, and handles up to 300 watts.

Radiation Resistance vs. Ohmic Resistance

Last month, I compared an antenna to a series-tuned circuit. Then I explained how its capacitive and inductive reactances could be canceled with an antenna tuner. Now let's look at the remaining part of the equation: the antenna's *radiation resistance*. This value is not what you measure with an ohmmeter (that's its DC *ohmic* resistance). Radiation resistance brings in AC conductivity of the feedline/cable, the antenna's element(s), and its associated ground system or radials. The radiation resistance of a good home/base station vertical is around 15 ohms, a whip on an auto is 1 or 2 ohms, and a beam antenna is between 15 and 30 ohms. Some form of step-up arrangement is (or should be!) used in each case to raise the radiation resistance to near 50 ohms.

"But the mobile whip on my auto doesn't have an impedance-matching section or transformer, and its SWR is only 1.4 to 1," you say? Hopefully, you simply overlooked how the matching component is integrated into the antenna system. Otherwise, a portion of your transceiver's output power is being dissipated as heat in the feedline/cable, ground system, and antenna wire/conductor. Don't fret: many of us have been living with radiation resistance-associated heat losses for a long time—and having a ball contacting nearly everyone we call.

Antenna Tuners: How They Work

Living with antenna variations and limitations and getting around them by using antenna tuners is a natural part of our amateur radio life. We often install an antenna at roof level rather than on a tower, for example, or we attach a whip to an auto's rear deck area rather than punching a mounting hole in the roof. Understanding how antenna tuners actually work lets us feel more comfortable and confident when using them.

In light this, I invited one of the leading manufacturers of antenna tuners, Martin F. Jue, K5FLU, President of MFJ Enterprises, Inc. to share some views of his tuners with us. First, let's look at the MFJ 921 shown in Photos A and B and in Figure 1. Martin explains his tuners as follows:

A dipole-type antenna can be represented by an inductor, capacitor, and resistor in series. Below resonance, the antenna looks like a resistor in series with a capacitor. Above resonance, the antenna looks like an inductor in series with a resistor. At resonance, the antenna looks like a resistor which may or may not be 50 ohms. The resistor represents the part of the antenna that accepts power from the transceiver and radiates it as radio waves.

By Dave Ingram, K4TWJ

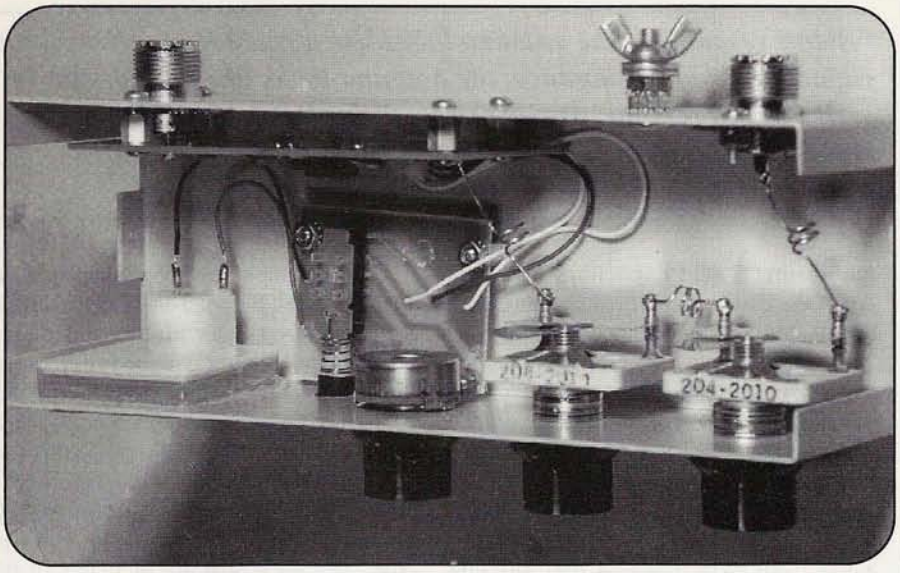


Photo B. Inside view of MFJ-921 2-meter/222-MHz antenna tuner. Note that only two-turn coils and two plates on capacitors are used for operation in VHF range. (Photos B through D courtesy David Branch, KB5VKY, of MFJ Enterprises, Inc.)

If an antenna is not resonant, it looks like inductive or capacitive reactance and may not be a good load for your transceiver. An antenna tuner cancels that undesired reactance and transforms the resistance to 50 ohms, which gives a 1:1 SWR for your transceiver.

Most antenna tuners for HF use a T-network because a Pi-network requires several thousand picoFarad of variable capacitance to produce a reasonable matching range. At VHF/UHF, however, the values of variable capacitance are small enough that a Pi-network can be used—and it reduces hand capacitance. MFJ goes a step further and uses dual Pi-L networks to further extend the tuning range and minimize hand capacitance in our VHF/UHF tuners.

Thanks for those words of wisdom, Martin. Now look behind the front panel of the MFJ 921 144/222-MHz antenna tuner shown in Photo B, and take a close look at its circuit diagram shown in Figure 1. Notice that the coils are not adjustable. How can you vary their inductance?

You start by using coils with more total inductance than needed, then canceling out the unneeded amount (for both the tuner and the antenna) with the adjustable

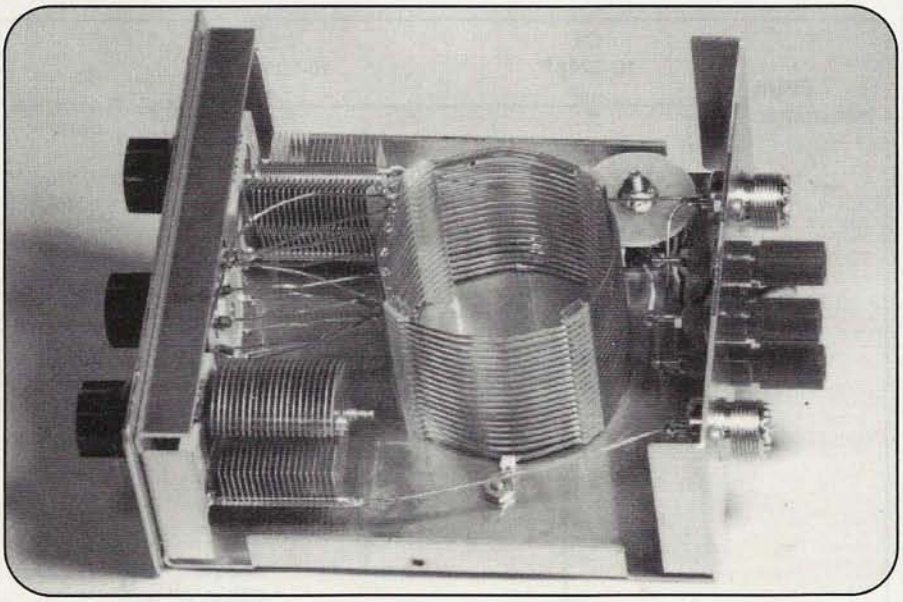


Photo C. The 300-watt MFJ-901B HF antenna tuner. This unit sports a T-network with tap-adjustable coil and variable input/output capacitors, as discussed in text. Compare the number of capacitor plates in this HF tuner with the VHF version in Photo B.

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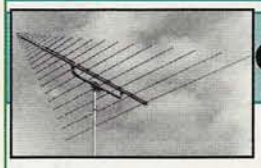

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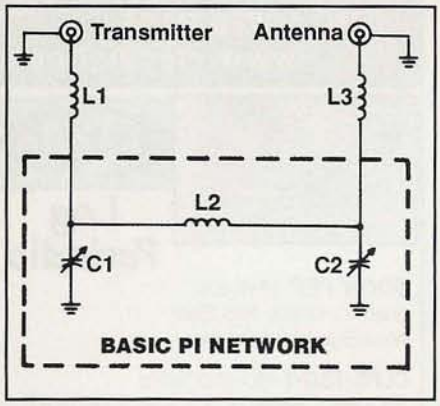

Figure 1. Circuit diagram of the MFJ-921 VHF antenna tuner. The section within dotted lines indicates a basic Pi-network. Coils outside the dotted line (L1 and L3) add additional inductance and make the tuner a dual Pi-L network. See additional discussion in text. (Diagrams courtesy MFJ)

capacitors. In other words, the inductive effects of L1, L2, and L3 can be set to any level by C1 and C2—or completely overridden so C1 and/or C2 add any desired amount of capacitive reactance. Neat, eh?

Now let's quickly discuss impedance matching. You'll remember from last month that I said capacitors can pass AC? OK, that explains how C1 can effectively connect L1 (and a part of L2) "across" the transceiver's output connector. Likewise, C2 can connect L3 (and a portion of L2) across the antenna's connector. As you adjust C1 and C2 to vary the inductance of L1, L2, and L3, you also electrically vary their turns ratio, producing step-up or step-down action! And you thought that antenna tuners were simply tuned circuits in a cabinet, eh? Surprise!

"Below resonance, the antenna looks like a resistor in series with a capacitor. Above resonance, the antenna looks like an inductor in series with a resistor. At resonance, the antenna looks like a resistor which may or may not be 50 ohms."—Martin F. Jue, President, MFJ Enterprises, Inc.

Differences in Antenna Tuners

Next, let's study the MFJ-901B HF (160 to 10-meter) antenna tuner shown in Photo C and Figure 2. As Martin pointed out, this tuner uses a T-network with an adjustable coil because exceptionally large (huge!) variable capacitors would be required to match a wide impedance range. Thus, an operator first makes a "ball park" adjustment with the coil, then fine-tunes (tweaks required input/output inductive or capacitive reactance) with the capacitors.

Compare the size of components in the MFJ 921 with the MFJ-901B. Notice that less capacity (fewer plates) and inductance (smaller coil(s) with fewer turns) are required for higher frequencies like 146 MHz, compared with 3.5 or 28 MHz. Next, compare the size of capacitors and the coil in the MFJ-901B—which will handle 300 watts—with the MFJ-989C (Photo D), that will handle 1500 watts. Note that wide spacing of plates in the '989C prevents arcing.

Unique Impedance Matching Concepts

Although seldom realized, a miniature form of tuner and impedance matching network is included in the base of many dual-band 2-meter/70-centimeter antennas. Consider, for example, the popular styles of 1/4 wavelength on 2 meters and 1/2 wavelength on 70 centimeters. The 2-meter section is low impedance and can present a suitable match—as is—to a handheld or to a transmission line connected to a mobile rig. The 70-centimeter section is high impedance, however, and requires a small inductor and capac-

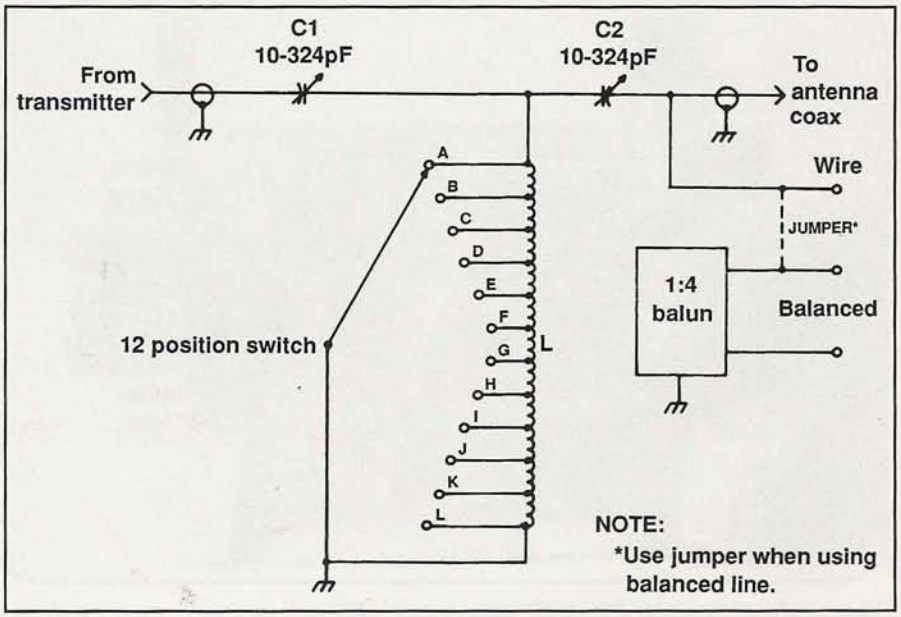

Figure 2. Circuit diagram of the MFJ-901B HF antenna tuner. Note that the positions of the capacitors and coil are reversed, in comparison to the MFJ-921, to yield a T-network.

Looking Ahead in

CQ VHF Ham Radio Above 50 MHz

Here are some of the articles that we're working on for upcoming issues of *CQ VHF*:

- "CQ VHF Review: Yaesu FT-847 HF/VHF/UHF/Satellite Transceiver," by Gordon West, WB6NOA
- "Mir Gets a TNC Upgrade (from Us)—Part 2," by Miles Mann, WF1F
- "Include 6 Meters in Your Field Day Station," by Ken Neubeck, WB2AMU
- "Rover Operating—Scottish-Style," by Simon Lewis, GM4PLM

Plus...

- "Repeater Timed Out...," by Rich Moseson, W2VU
- "Make Project Labels with Your PC...on Paper," by Raymond Schneider, W6JXW

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Technically Speaking

Antenna tuners are great for ensuring that your rig "sees" a low SWR, especially when inclement weather discourages outdoor "dink sessions." Before installing a tuner, however, take a few minutes to be sure that it's not being used to cover up a problem that should be corrected.

Compare your antenna's SWR with its manufacturer's specs and try to determine why it's higher than normal. Is the antenna mounted exceptionally close to other metallic objects? Are its elements the right length? Are element joints shiny clean or corroded with age or exposure to salt water spray? Is the antenna's connecting coax cable old and brittle? Has its outer vinyl jacket been nicked/broken open? Are the coax connectors solid and fully waterproofed (very important—rain can be drawn into an unprotected connector, travel inside the coax, and render the cable useless in only a couple of months time)? Simply wrapping a connector with electrical tape is *not* waterproofing it. Using a heavy coat of silicone or hand-moldable Coax Seal to enclose all the connection area and an inch of the coax cable is highly recommended.

All of the previous factors can cause high SWR that can be reduced with a tuner—but signal losses will still exist. On the other hand, if your antenna's SWR is, say, 2.2:1 at 144.050 MHz and 1.5:1 at 147.000 MHz, it's probably mistuned or mildly affected by nearby objects and a tuner easily solves the problem.

itor in an "L" network for matching. The necessary values are very small at 440 MHz and generally equate to a curved wire positioned between two pieces of metal. If you have ever "dissected" a dual-band antenna, you've probably seen those components but assumed they were parts of the base mount. Although the network is simple, it performs its duty on 70 centimeters. It also appears "transparent" at 2 meters. In other words, 145-MHz signals do not electrically "see" the network. Again, pretty neat.

Switching to Power Supplies

Our discussion of antenna tuners could continue indefinitely (isn't it amazing what only two components can do!), but

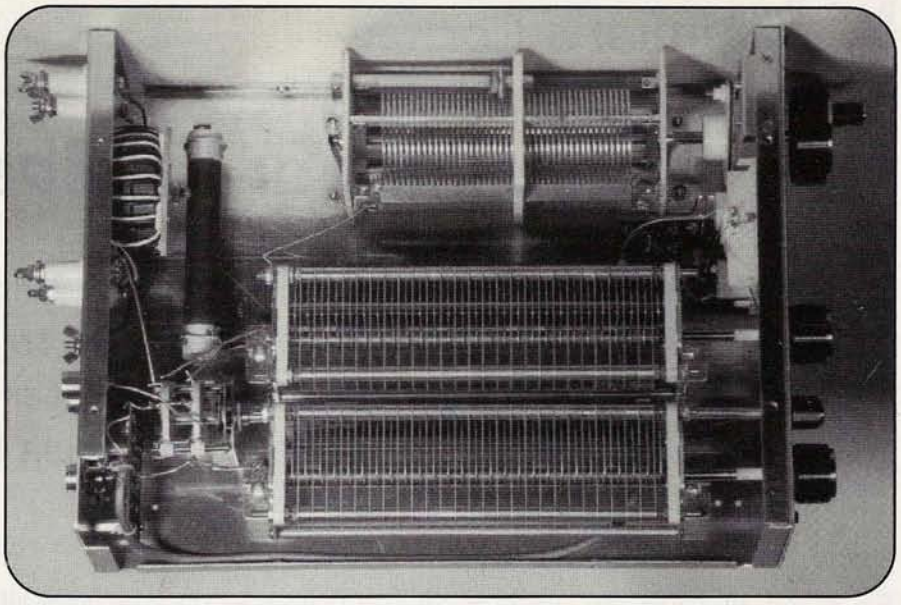

Photo D. Inside view of "Big Daddy" MFJ-989C reveals variable capacitors with approximately the same capacity as MFJ-901B, but with larger size and wider spacing between plates to handle 1500 to 3000 watts.

I'm out of space for now. Hopefully, I shed some light on antenna tuners that will help you understand them. Next month, I'll continue with another application of capacitors and coils, and an interesting discussion on how power supplies work. Stay tuned! 73,

Dave, K4TWJ

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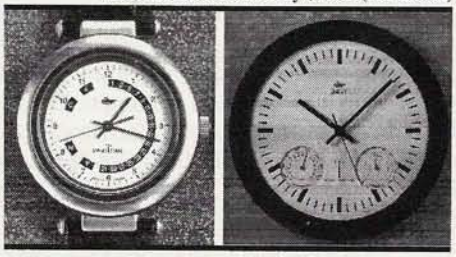

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